

# First Direct Double-Beta Decay $Q$ -value Measurement of $^{82}\text{Se}$ in Support of Understanding the Nature of the Neutrino

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In anticipation of results from current and future double-beta decay studies, we report a measurement resulting in a  $^{82}\text{Se}$  double-beta decay  $Q$ -value of 2997.9(3) keV, an order of magnitude more precise than the currently accepted value. We also present preliminary results of a calculation of the  $^{82}\text{Se}$  neutrinoless double-beta decay nuclear matrix element that corrects in part for the small size of the shell model single-particle space. The results of this work are important for designing next generation double-beta decay experiments and for the theoretical interpretations of their observations.

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The results of recent neutrino oscillation experiments indicate that the mass of the neutrino is non-zero [1–3]. The mass hierarchy and the absolute mass scale of the neutrino, however, are unknown. Furthermore, the nature of the neutrino is also unknown; is it a Dirac or Majorana particle, i.e. is the neutrino its own antiparticle? The only known practical method for determining the nature of the neutrino is through neutrinoless double-beta decay ( $0\nu\beta\beta$  decay) measurements [4]. Interest in double-beta decay ( $\beta\beta$  decay) has been increasing since the laboratory verification of the weak, but allowed, two-neutrino double-beta decay ( $2\nu\beta\beta$  decay) of  $^{82}\text{Se}$  [5]. Including laboratory, geochemical, and radiochemical experiments, twelve isotopes have been observed to undergo  $2\nu\beta\beta$  decay:  $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{128}\text{Te}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$ ,  $^{238}\text{U}$ , and  $^{130}\text{Ba}$  [6, 7]. With the exception of the controversial claim in Ref. [8],  $0\nu\beta\beta$  decay has yet to be observed. If experiments succeed in observing  $0\nu\beta\beta$  decay, we would have evidence that the neutrino is a Majorana particle and that conservation of total lepton number is violated — a situation forbidden by the standard model of particle physics.

An extensive campaign is currently underway to develop next-generation experiments to detect  $0\nu\beta\beta$  decay in a number of candidate isotopes (see Ref. [9] for a current review of planned experiments). One such experiment, SuperNEMO, is expected to provide an increase in sensitivity of three orders of magnitude over its predecessor, NEMO-III, and is projected to reach a half-life sensitivity at the 90% confidence level of  $1\text{--}2 \times 10^{26}$  years by observing 100–200 kg of  $^{82}\text{Se}$  for five years [9, 10].

The defining observable of  $0\nu\beta\beta$  decay is a single peak in the electron sum-energy spectrum at the  $\beta\beta$  decay

$Q$ -value,  $Q_{\beta\beta}$ . Hence, it is crucial to have an accurate determination of  $Q_{\beta\beta}$ . The  $Q$ -value is also a key parameter required to determine the phase space factor (PSF) of the decay. The effective Majorana neutrino mass, together with the corresponding PSF and nuclear matrix element (NME) for a  $0\nu\beta\beta$  decay candidate provide the necessary information to determine the  $0\nu\beta\beta$  decay half-life, which is given by:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}^5, Z)|M_{0\nu}|^2(\langle m_{\beta\beta} \rangle / m_e)^2, \quad (1)$$

where  $M$  is the relevant NME,  $\langle m_{\beta\beta} \rangle$  is the effective Majorana mass of the neutrino,  $m_e$  is the mass of the electron, and  $G_{0\nu}$  is the PSF for the  $0\nu\beta\beta$  decay, which is a function of  $Q_{\beta\beta}^5$  and the nuclear charge,  $Z$ . Thus, to obtain an accurate estimation of the half-life sensitivity needed to detect a given  $\langle m_{\beta\beta} \rangle$ , or conversely, to determine  $\langle m_{\beta\beta} \rangle$  if the half-life is measured, the NME and especially the  $Q$ -value need to be known to high precision.

Of all the  $0\nu\beta\beta$  decay candidates currently employed in experiments,  $^{82}\text{Se}$  is the only one whose  $Q$ -value has not been measured directly through high-precision Penning trap mass spectrometry (PTMS). PTMS has proven itself to be the most precise and accurate method for determining atomic masses and therefore,  $Q$ -values [11]. In some cases  $Q_{\beta\beta}$ -values determined prior to direct Penning trap measurements have been found to be off by more than ten keV [12, 13]. Furthermore, careful calculations of the NME for  $^{82}\text{Se}$   $0\nu\beta\beta$  decay [14–18] differ from one another by more than a factor of two. In this letter, in anticipation of SuperNEMO and other possible experiments with  $^{82}\text{Se}$ , we present the results of a direct measurement of  $Q_{\beta\beta}$  with the Low-Energy Beam and Ion

Trap (LEBIT) PTMS facility and results to improve shell model calculations of the NME.

The direct  $Q_{\beta\beta}$  measurement for  $^{82}\text{Se}$  was carried out at the National Superconducting Cyclotron Laboratory (NSCL) using LEBIT, a Penning trap mass spectrometer facility for high precision mass measurements on isotopes produced via projectile fragmentation [19]. We used the plasma ion source of the LEBIT facility to simultaneously produce ions of  $^{82}\text{Se}$  and of the  $\beta\beta$  decay daughter,  $^{82}\text{Kr}$ . The source was equipped with a ceramic charge holder and was filled with  $\sim 200$  mg of granulated selenium which was vaporized by the heat from the ion source filament. A helium support gas for the source was mixed with a small amount of krypton to obtain a similar beam current of  $^{82}\text{Kr}^+$  to  $^{82}\text{Se}^+$  within a factor of three. The extracted ion beam was guided through a radio-frequency quadrupole (RFQ) mass filter to suppress the strong accompanying helium current before injection into a cryogenic RFQ beam cooler and buncher for the creation of short low-emittance ion bunches that are sent to the LEBIT 9.4 T Penning trap [20]. On their path the ions were purified further by using a time-of-flight mass separation scheme [21], allowing only ion species of the same mass-to-charge ratio to be dynamically captured in the trap.

At LEBIT, the cyclotron frequency,  $\nu_c = qB/2\pi m$ , of an ion with mass-to-charge ratio,  $m/q$ , in a magnetic field,  $B$  is measured using the Time-of-Flight (TOF) ion-cyclotron resonance detection technique [22, 23]. First, isobaric contaminants are removed from the Penning trap by driving them to large radial orbits with a radio frequency (RF) azimuthal dipole field. To measure  $\nu_c$ , the trapped ions are exposed to an azimuthal quadrupole RF field at a frequency  $\nu_{RF}$  near their cyclotron frequency with the appropriate RF amplitude and excitation time [22, 23]. After ejection from the trap, the ions travel through the inhomogeneous section of the magnetic field, where the energy of the ions' radial motion is transferred to the axial direction [24], and are detected on a micro-channel plate (MCP) detector. In resonance, i.e.,  $\nu_{RF} = \nu_c$ , the energy pickup of the ions' radial motion is maximized and their TOF to the MCP is minimized [22]. For a cyclotron frequency determination, this cycle of trapping, excitation, ejection, and TOF measurement is repeated for different frequencies. This leads to cyclotron resonance curves, as shown in Figure 1, with a centroid at  $\nu_c$ .

The measurement process for the determination of  $Q_{\beta\beta}(^{82}\text{Se})$  consisted of alternating cyclotron frequency measurements of  $^{82}\text{Kr}^+$  and  $^{82}\text{Se}^+$ . These measurements were performed in a series of four runs. The first run consisted of measurements using a 500 ms excitation time. For increased precision, we utilized a 750 ms excitation time for the final three runs. Each TOF resonance was the average of 25 to 40 scans over the respective frequency range with 41 trapping cycles per scan. During

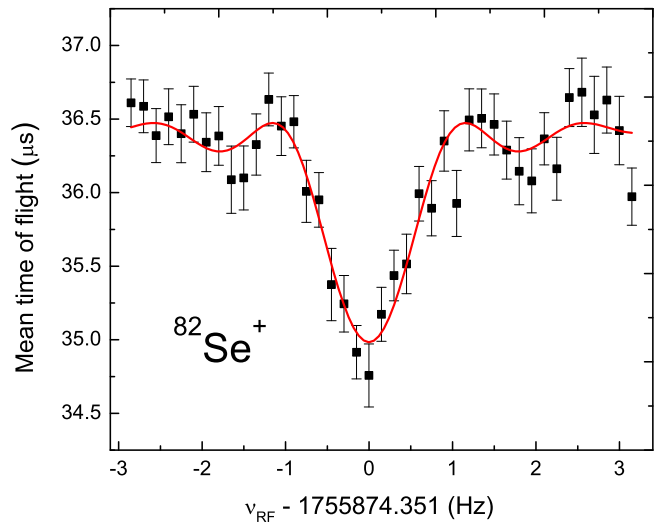


FIG. 1. (color online). Time-of-flight cyclotron resonance curve for  $^{82}\text{Se}^+$ . An excitation time of  $T_{RF} = 750$  ms was used to obtain a resolving power of  $2 \times 10^6$ . The fit of the theoretical line shape to the data is represented by the solid line.

the measurement process the number of ions recorded by the MCP was limited to an average of 2 ions per trapping cycle, corresponding to  $< 7$  ions in the trap at a time (assuming 30% detector efficiency). This was done to limit the number of contaminant ions produced via charge-exchange reactions. Each resonance consisted of  $\sim 500$  to 3000 detected ions, depending on the number of scans per resonance and the beam current from the ion source. To determine  $\nu_c$ , each resonance was fitted using the theoretical line shape described in Ref. [22]. The average uncertainty in  $\nu_c$  for each resonance was  $\sim 30$  ppb (parts per billion).

For the frequency ratio determination of  $^{82}\text{Kr}^+$  to  $^{82}\text{Se}^+$ , drifts in the magnetic field were taken into account by linearly interpolating two cyclotron frequency measurements of  $^{82}\text{Kr}^+$  bracketing a  $^{82}\text{Se}^+$  measurement to obtain  $\nu_c^{int}(^{82}\text{Kr}^+)$ . This interpolated cyclotron frequency was used to obtain the frequency ratio  $R = \nu_c^{int}(^{82}\text{Kr}^+)/\nu_c(^{82}\text{Se}^+)$ . The values obtained from a total of 110 ratio determinations and their weighted average are shown in Figure 2. The difference to the reference ratio,  $R_{AME2003} = [m(^{82}\text{Kr}) - m_e]/[m(^{82}\text{Se}) - m_e]$ , is plotted using the mass values for  $^{82}\text{Kr}$  and  $^{82}\text{Se}$  from the atomic mass evaluation AME2003 [25].

In preparation for, and during the measurement process, great care was taken to minimize possible systematic effects. By measuring mass doublets, contributions to the measurement uncertainty arising from mass dependent systematic effects due to frequency shifts, for example caused by field imperfections, are already greatly reduced. Nevertheless, prior to the measurements, im-

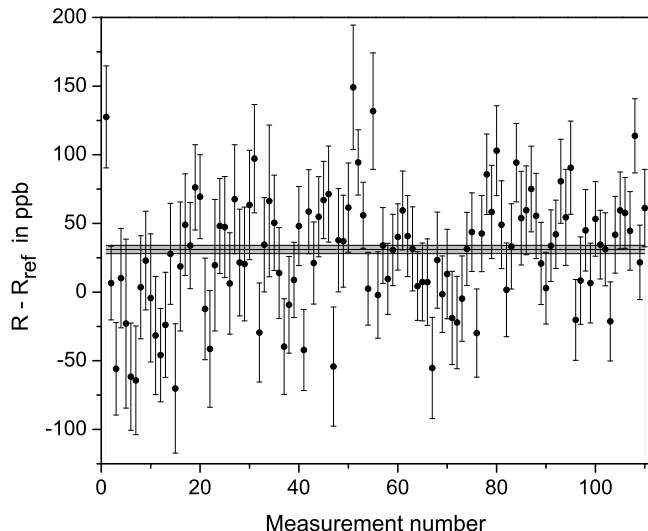


FIG. 2. Difference between the cyclotron frequency ratio of  $^{82}\text{Kr}^+$  and  $^{82}\text{Se}^+$  and the ratio obtained from literature mass data [25]. The solid lines indicate the weighted average and the  $1\sigma$  statistical uncertainty band.

perfections were carefully minimized following a tuning procedure described in Ref. [26].

The effect of a non-linear magnetic field drift is not accounted for in the data evaluation and is not mitigated by using a mass doublet. Therefore the cyclotron frequency measurements of  $^{82}\text{Kr}^+$  and  $^{82}\text{Se}^+$  were alternated with a period of no greater than 1 hour. Based on an earlier study [27], this should lead to residual systematic effects of the cyclotron frequency ratio no larger than 1 ppb. This uncertainty was further minimized by stabilizing the pressure in the liquid helium dewar to 10 ppm (parts per million) [28], resulting in an uncertainty well below 1 ppb. Simultaneously trapped ions of a different  $m/q$  value [29] can cause frequency shifts — this effect was minimized by verifying that contaminant ions were never present at a level exceeding a few percent, low enough to not lead to a significant shift at the desired precision.

The weighted average of the ratios for the individual runs and the corresponding statistical uncertainty are listed in Table I together with the weighted average  $R_{\text{LEBIT}}$  of all results and the value  $R_{\text{AME2003}}$  obtained with mass data from AME2003 [25]. Through evaluation of the entire data set, with statistical errors as obtained from the fits of theoretical lineshapes to the measured cyclotron resonance curves, we determined a Birge ratio [30] of 1.27(5). While close to unity, the significant deviation indicates the presence of residual systematic effects at the 0.8 ppb level not discovered in the individual measurements or in the tests for systematic effects performed. Therefore, to account for these non-statistical contributions we multiply the statistical uncertainty of the weighted average  $R_{\text{LEBIT}}$  for all data by the value of

TABLE I. Average cyclotron frequency ratios  $R_{\text{run}} = \nu_c^{\text{int}}(^{82}\text{Kr}^+)/\nu_c(^{82}\text{Se}^+)$  with their statistical errors as obtained in four separate runs with  $N$  frequency ratio measurements performed in each run. Also given is the final weighted average  $R_{\text{LEBIT}}$  with its statistical and final uncertainty and the ratio based on the AME2003 atomic mass evaluation [25].

Run	N	$R_{\text{run}}$
1	53	1.000 039 285(5)
2	2	1.000 039 30(2)
3	7	1.000 039 29(1)
4	48	1.000 039 290(4)
$R_{\text{LEBIT}}$		1.000 039 290(4)(5)
$R_{\text{AME2003}}$		1.000 039 26(3)

the Birge ratio. Both the statistical and total uncertainty for  $R_{\text{LEBIT}}$  are given in the table.

The  $\beta\beta$  decay  $Q$ -value is determined from the mass difference between the mother nuclide of mass  $m_m$  and daughter nuclide of mass  $m_d$  through:

$$Q_{\beta\beta}/c^2 = m_m - m_d = (R - 1)(m_d - m_e), \quad (2)$$

where  $R$  is the cyclotron frequency ratio between the singly charged ions of the daughter and mother nuclides,  $c$  is the speed of light, and  $m_e$  accounts for the missing electron mass of singly charged ions used in the measurement. Using our final frequency ratio  $R_{\text{LEBIT}}$  and the AME2003 mass for  $^{82}\text{Kr}$  we obtain,  $Q_{\beta\beta} = 2\,997.9(3)$  keV. The new LEBIT  $Q$ -value is nearly an order of magnitude more precise than the previous value of  $Q_{\beta\beta} = 2\,996(2)$  keV based on mass data from [25], a dramatic improvement to one of the ingredients needed for a better determination of the half-life limit for  $0\nu\beta\beta$  decay in  $^{82}\text{Se}^+$ .

In addition to a precise  $Q_{\beta\beta}$ -value, an accurate NME for the decay is also needed. A number of methods have been applied to the NME problem, and in  $^{82}\text{Se}$  one of the most prominent methods — the shell model [14, 15] — gives matrix elements that are less than half the size of those produced by the quasiparticle random phase approximation (QRPA) [16], the Interacting Boson Model [17], and the Generator Coordinate Method [18]. Each approach has its strengths and weaknesses; for instance, the shell model incorporates complicated correlations but only in a small single-particle space (the valence shell), while the QRPA is applied in large single-particle spaces but includes only simple correlations. Here we report an attempt to correct for the shell model deficiency by calculating an effective  $0\nu\beta\beta$  decay operator that implicitly includes effects of single-particle levels that are outside the valence shell.

Our calculation, which will be described in detail in a forthcoming publication [31], uses diagrammatic perturbation theory to construct an effective two-body

TABLE II.  $^{82}\text{Se}$   $0\nu\beta\beta$  decay matrix elements calculated in QRPA, standard shell model (SM), and with the effective  $0\nu\beta\beta$  decay operator discussed in the text.

QRPA [16]	SM [15]	Corrected SM
5.19	2.64	3.56

$0\nu\beta\beta$  decay operator that, together with an effective Hamiltonian, allows the shell model to get around its truncations when the procedure is carried to completion [32, 33]. This framework has been used extensively to determine effective valence-space interactions, but much less so to construct other effective operators. The only existing work on an effective  $0\nu\beta\beta$  decay operator is an exploratory calculation, as it happens, for  $^{82}\text{Se}$  [34]. In that work the starting point was a  $G$ -matrix interaction [33]. Using a low-momentum interaction [35],  $V_{\text{low } k}$ , derived from nuclear forces in chiral effective field theory [36], we have carried this calculation significantly further. We now include all diagrams to second order in the interaction, state norms, and folds, while expanding the set of high-lying single-particle orbits that we treat.

Our result is shown in Table II, which we compare to values obtained from QRPA and the standard shell model. The contributions from outside the valence space to the effective operator increase the shell model NME by  $\sim 30\%$  to 3.56, narrowing the gap between it and the QRPA.

This calculation represents an important first step in producing a true *ab initio* NME, suggesting that it will be larger than the shell model has indicated. We plan to improve our results by including three-nucleon forces [37–39] and two-body currents [40], by constructing an effective interaction consistent with the effective decay operator, and by investigating the size of induced three-body terms in the effective decay operator.

In conclusion, by using Penning trap mass spectrometry we have performed the first direct  $Q$ -value measurement of  $^{82}\text{Se}$   $\beta\beta$  decay by measuring the cyclotron frequency ratio between singly charged ions of  $^{82}\text{Se}$  and the  $\beta\beta$  decay daughter,  $^{82}\text{Kr}$ . Our result,  $Q_{\beta\beta} = 2\,997.9(3)$  keV, is nearly an order of magnitude more precise than the previous value based on the 2003 atomic mass evaluation [25]. Following the procedure in Ref. [41] and using our new  $Q$ -value, we calculate the PSF for the  $0\nu\beta\beta$  decay mode of  $^{82}\text{Se}$  to be  $G_{0\nu} = 2.848(1) \times 10^{-14} \text{ yr}^{-1}$ , where the uncertainty has also been improved by nearly an order of magnitude. With the corrected shell model NME calculation presented here and the current upper limits of  $\langle m_{\beta\beta} \rangle = 140 - 380$  meV from the EXO-200 experiment [42] we obtain a lower limit range for the  $^{82}\text{Se}$   $0\nu\beta\beta$  decay half-life of  $5.0 \times 10^{24} - 3.7 \times 10^{25}$  years. Assuming SuperNEMO achieves its projected sensitivity at

the 90% confidence level of  $1\text{--}2 \times 10^{26}$  years, an effective neutrino mass as low as 60–85 meV could be detected.

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